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Performance Analysis of Reflectarray Resonant Elements based on Dielectric Anisotropic Materials

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Abstract

This paper presents a thorough investigation of the relationship between reflection loss and dynamic phase distribution performance of three different reflectarray resonant elements. The tunability characteristics of rectangular, dipole and ring elements printed on grounded non-linear dielectric anisotropic substrates have been investigated at X-band frequency range using CST computer model. A detailed analysis of reflection loss and dynamic phase range, with respect to dielectric anisotropy is presented for different anisotropic liquid crystal substrate materials. Preliminary analysis results show that ring element offers the highest reflection loss and dynamic phase range of 56.54 dB and 248° respectively compared to rectangular element which offers 10.74 dB and 90° respectively. Furthermore the rectangular element attains a maximum frequency tunability of 796 MHz compared to ring element which attains 716 MHz. Moreover it has also been shown that an increase in dielectric anisotropy of non-linear materials affect dynamic phase ranges and frequency tunability of three resonant elements.

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Keywords: reflectarrays; resonant elements; dynamic phase range; frequency tunability.

1. Introduction

Antennas have an important role in the field of communications to exchange the information at a distance. Parabolic antenna is the main consideration for communication purposes since last few decades but due to its curved surface and bulky structure, researchers are always in search of a better alternative solution. Therefore a flat surface reflectarray antenna is gaining importance because of its lower cost and smaller size. It consists of printed reflecting elements on a grounded flat dielectric surface, illuminated by a feed antenna [1]. It can be designed to have very high gain with relatively good efficiency, as well as to have its main beam scanned to large angles from its broadside direction [2]. But due to its loss performance and narrower bandwidth its applications are limited, especially in radar and satellite communications [3]. These limitations can be decreased by the selection of a suitable reflecting element with proper dielectric substrate [4], [5]. Liquid crystal materials can be realized as a dynamic phase control strategy in reflectarrays due to their non-linear dielectric properties [6, 7]. In this work various types of non-linear liquid crystal substrate materials, listed in Table I, are used to design different types of X-band reflectarray patch elements namely rectangular, dipole and ring, printed on 1mm thick anisotropic substrate resonating at 10 GHz.

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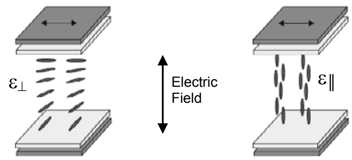

Fig. 1. Design configuration of unit cell reflectarray element with different resonant elements

TABLE 1 NON-LINEAR LIQUID CRYSTAL SUBSTRATE MATERIALS

Anisotropic LC Materials	$\varepsilon_\perp$	$\varepsilon_\parallel$	**Dielectric Anisotropy ($\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$)**	**tanδ⊥**	**tanδ‖**
K15 Nematic	2.1	2.27	0.17	0.072	0.06
Merck BL037	2.25	2.45	0.2	0.048	0.025
Chisso JB-1017	2.5	2.9	0.4	0.015	0.005
LC-B1	2.6	3.05	0.45	0.022	0.007

The numerical Finite Integral Method (FIM) has been used to investigate the reflection loss and dynamic phase range characteristics by using commercially available CST computer model.

2. Dielectric Anisotropic Materials

Non-linear dielectric materials are also called dielectric anisotropic materials. Anisotropy means materials which have variation in values of a property in any direction. Dielectric anisotropic materials have a non-linear or variable dielectric permittivity "ε" [8]. It is possible to vary the dielectric permittivity of anisotropic materials simply by applying a dc voltage across the substrate [9], which allows the molecules of anisotropic material to be oriented parallel to the incident field and attain maximum dielectric permittivity value ($\varepsilon_\parallel$). Where as without a dc voltage molecules of anisotropic material are oriented perpendicular to the incident field and material attains a minimum dielectric permittivity value ($\varepsilon_\perp$) [10] as shown in Fig. 1. Table I summarizes the properties of non-linear dielectric materials that are used to design the reflectarray resonant elements. The tunability capability in dielectric permittivity is required in order to realize dynamic phase distribution of reflectarrays. The difference between maximum and minimum value of dielectric permittivity is called dielectric anisotropy of material and is given by equation (1).

$$\Delta\varepsilon = \varepsilon \parallel - \varepsilon \perp \tag{1}$$

Where, $\Delta\varepsilon$ = Dielectric anisotropy

$\varepsilon_\parallel$ = Dielectric constant with applied DC voltage

$\varepsilon_\perp$ = Dielectric constant without DC voltage

3. Results and Discussion

The non-linear dielectric materials have a range of dielectric permittivity values. Therefore in this work, the minimum ($\varepsilon_\perp$) and maximum ($\varepsilon_\parallel$) dielectric permittivity values are considered for each material, so each material holds two different values for reflection loss and reflection phase, operating at 10 GHz.

3.1 Reflection Loss And Frequency Tunability

The reflectivity performance of reflectarray resonant elements based on a selected anisotropic material named LC-B1 is shown in Fig. 2. As depicted in Fig. 2, it has been observed that ring element is observed to offer a maximum reflection loss performance of 7.92 dB as compared to dipole and rectangular elements which offer 7.19 dB and 3.54 dB respectively. This is because the rectangular element has a wider reflecting area as compared to dipole and ring elements respectively.

Therefore rectangular element reflects back most of the incident energy and offers lowest reflection loss performance. On the other hand due to narrower reflecting area of ring element most of the incident energy interacts with the substrate region and as a result highest reflection loss is obtained. Table II contains the maximum reflection loss values of all anisotropic substrate materials that are used to design different reflectarray resonant elements. It has been observed from Table II that among all listed materials, K-15 nematic offers the highest reflection loss performance of 10.74 dB, 33.51 dB and 56.54 dB for rectangular, dipole and ring elements respectively. Alternatively Chisso offers the lowest reflection loss performance of 2.36 dB, 4.76 dB and 5.12 dB respectively. The reason behind that is, K-15 nematic has a maximum dissipation factor or tangent loss value of 0.072 whereas Chisso has 0.005 which leads to lower reflection losses.

A change in the dielectric permittivity of dielectric anisotropic materials can also cause a significant change in resonant frequency that is known as frequency tunability. Table III summarizes the frequency tunability values for rectangular, dipole and ring elements printed above different anisotropic LC materials. It has been shown from Table III that, as the dielectric anisotropy increases from 0.17 to 0.45 the frequency tunability also increases from 372–796 MHz, 364–784 MHz and 360–716 MHz for rectangular, dipole and ring elements respectively. Frequency tunability response of reflectarray resonant elements corresponds to the flexibility in the value of dielectric anisotropy of anisotropic materials.

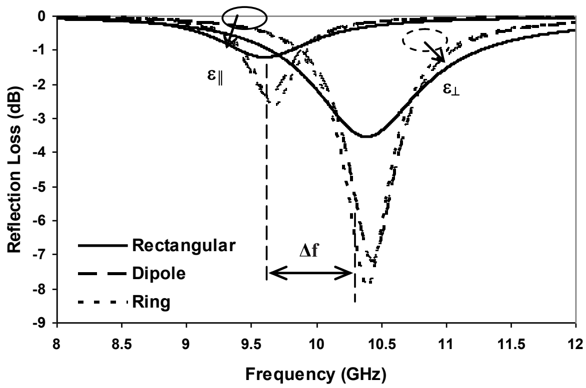

Fig. 2. Reflection loss performance of different resonant elements

Table 2:Maximum reflection loss performance of reflectarray resonant elements

Anisotropic LC Materials	Δε	Maximum Reflection Loss (dB) Rectangular	Dipole	Ring
K15 Nematic	0.17	10.74	33.51	56.54
BL037	0.2	7.11	18.52	22.69
Chisso JB-1017	0.4	2.36	4.76	5.12
LC-B1	0.45	3.54	7.19	7.92

Table 3: Frequency Tunability of different reflectarray resonant elements

Anisotropic LC Materials	Δε	Frequency Tunability (Δf) (MHz) Rectangular	Dipole	Ring
	0.17	372	364	360
	0.2	404	360	320
Chisso JB-1017	0.4	736	724	688
LC-B1	0.45	796	784	716

3.2 Dynamic Phase Range

Non-linear dielectric materials attain a range of dielectric constant values from minimum ($\varepsilon_\perp$) to maximum ($\varepsilon_\|$). Therefore when a non-linear dielectric material is used as a reflectarray substrate a phase agile characteristic occurs which is known as dynamic phase distribution. The maximum phase variations of the reflected signal occur at resonant frequency. Dynamic phase range can be defined as.

$$\Delta\varphi = \varphi(\varepsilon\|) - \varphi(\varepsilon\perp) \quad (2)$$

The dynamic phase range of LC materials is a measure of dielectric anisotropy. Fig. 3 shows the dynamic phase ranges for rectangular and dipole elements printed on LC-B1 anisotropic material. As shown in Fig. 3, it has been observed that ring element is observed to offer a maximum dynamic phase range of 248° as compared to dipole and rectangular elements which offer 238° and 160° respectively. Table IV contains the values of dynamic phase ranges for different resonant elements printed on 1 mm thick dielectric anisotropic materials. It has been observed from Table IV that, as the dielectric anisotropy increases from 0.17 to 0.45 the dynamic phase range also increases from 90°–160°, 195°–238° and 200°–248° for rectangular, dipole and ring elements respectively. Furthermore LC-B1 is observed to offer a wider dynamic phase range performance of 160°, 238° and 248° for rectangular, dipole and ring elements respectively compared to K-15 nematic which offers 90°, 195° and 200° respectively. This is because the resonant elements having higher reflection losses contribute steeper reflection phases as compared to those, having lower reflection losses [4], which corresponds to wider dynamic phase ranges as in the case of ring element.

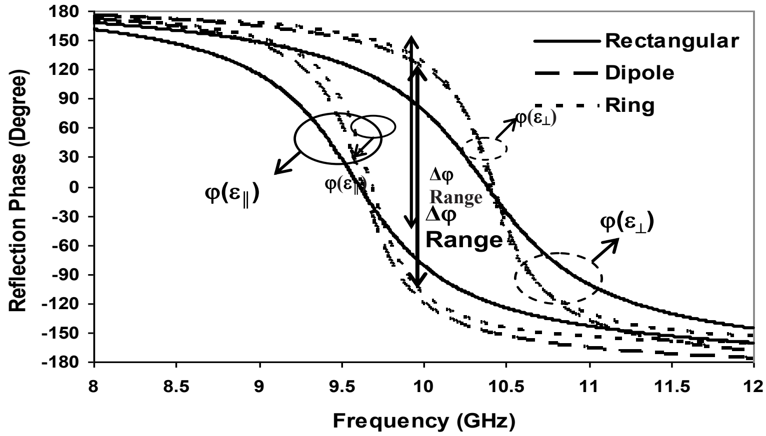

Fig. 3. Dynamic Phase Ranges (a) Rectangular Element (b) Dipole Element

Table 4 Dynamic Phase Range Of Rectangular and Dipole Elements

Anisotropic LC Materials	$\Delta\varepsilon$	Dynamic Phase Range (°) Rectangular	Dipole	Ring
K15 Nematic	0.17	90	195	200
BL037	0.2	90	160	193
Chisso JB-1017	0.4	150	228	231
LC-B1	0.45	160	K15 Nematic	248
			BL037	

4. Conclusion

A detailed analysis based on Finite Integral Method, presented in this work demonstrates that a suitably selected material can increase the phase range performance of reflectarray which is required to realize a progressive phase distribution. Moreover different types of resonating patch elements such as ring, dipole and rectangular can also enhance the performance of reflectarray antenna mainly in wider phase ranges and higher frequency tunability. Dielectric anisotropic materials are shown to offer a rapid dynamic phase change behavior for designing an electronically tunable reflectarray antenna. It has been shown that the dielectric anisotropy of non-linear materials can affect the tunability performance of reflectarray resonant elements. Further more materials having high dielectric anisotropy values also offer higher dynamic phase ranges. It has been concluded that the ring element with wider dynamic phase range and rectangular element with higher frequency agility are useful particularly for radar and earth observatory systems.

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